

# Do we have three $S_{11}$ resonances in the second resonance region?

Zhenping Li<sup>1</sup> and Ron Workman<sup>2</sup>

<sup>1</sup>Physics Department, Carnegie-Mellon University  
Pittsburgh, PA. 15213-3890

<sup>2</sup>Department of Physics  
Virginia Polytechnic Institute and State University  
Blacksburg, VA. 24061

February 9, 2008

## Abstract

We review the status of the  $S_{11}$   $N^*$  resonances in light of some recent theoretical and phenomenological results. Whereas the quark model predicts two such resonances around 1.6 GeV, there is considerable evidence for a third  $S_{11}$  resonance in this energy range. This suggests that a  $K\Sigma$  or  $K\Lambda$  quasi-bound state may indeed exist below the kaon production threshold. We show that kaon production experiments, in particular  $K^0$  photoproduction off nucleons, would be very sensitive to the existence of the third  $S_{11}$  resonance.

PACS Numbers: 11.80.Et, 12.39.Fe, 13.60.Le, 13.75.Gx

There has been considerable progress recently in the investigation of pion-nucleon scattering and meson-photoproduction off nucleons to extract the properties of baryon resonances. The partial wave analysis of  $\pi N$  elastic scattering data to 2.1 GeV has been updated by the VPI group[1], and a coupled channel analysis of  $\pi N \rightarrow \eta N$  and  $\eta N \rightarrow \eta N$  has also been published[2]. In addition to these renewed analyses, new experimental data for  $\eta$  photoproduction in the threshold region from Bates[3], the Bonn accelerator ELSA[4], and the Mainz accelerator MAMI[5] have been published. These data play a unique role in extracting the properties of the  $S_{11}(1535)$  resonance. In particular, new data from Mainz provide us with more systematic information on  $\eta$  production near threshold, with much better energy and angular resolution. This enables us to determine the properties of the  $S_{11}(1535)$  resonance more precisely. On the theoretical side, a new approach based on the chiral quark model has been developed for meson photoproduction[6, 7, 8], and the particular case of  $\eta$  photoproduction off nucleons[7] has been investigated in this new approach. The chiral quark model for meson photoproduction starts from the low energy QCD Lagrangian[9] so that the meson-quark interaction is chiral invariant and the low energy theorem[10] for threshold pion photoproduction is automatically recovered. This establishes a connection between the reaction mechanism in photoproduction and the fundamental theory (QCD). Perhaps more importantly, it relates the photoproduction data directly to the spin-flavor structure of baryon resonances. In this paper, we will focus on properties of the  $S_{11}$  resonances, and highlight possible physical consequences.

One property of the  $S_{11}(1535)$  resonance, determined from  $\eta$  photoproduction, is given by the quantity  $\xi$ ,

$$\xi = \sqrt{\frac{M_N k \chi_{\eta N}}{q M_R \Gamma_T}} A_{\frac{1}{2}} \quad (1)$$

where  $M_N$  ( $M_R$ ) denotes the mass of the nucleon (resonance),  $k$  and  $q$  correspond to the momenta of the incoming photon and the outgoing meson  $\eta$ ,  $\chi_{\eta N}$  is the branching ratio of the resonance to the  $\eta N$  channel, and  $\Gamma_T$  and  $A_{\frac{1}{2}}$  are the total width and the helicity amplitude for the resonance. A study[11] by the RPI group shows that this quantity obtained from the experimental data is model independent, and thus should be calculated in theoretical investigations. One advantage of the chiral quark model approach is that the quantity  $\xi$  for the  $S_{11}(1535)$  resonance can be directly related to its underlying spin flavor structure, which is expressed by the analytical form

$$\xi = \sqrt{\frac{\alpha_\eta \alpha_e \pi (E^f + M_N)}{M_R^3} \frac{C_{S_{11}(1535)} k}{6 \Gamma_T} \left[ \frac{2 \omega_\eta}{m_q} - \frac{2 q^2}{3 \alpha^2} \left( \frac{\omega_\eta}{E^f + M_N} + 1 \right) \right]}$$

$$\left(1 + \frac{k}{2m_q}\right) e^{-\frac{q^2+k^2}{6\alpha^2}}, \quad (2)$$

where  $\omega_\eta$  and  $E^f$  are the energies of the outgoing  $\eta$  meson and the nucleon,  $m_q = 0.34$  GeV is the constituent quark mass, and  $\alpha^2 = 0.16$  GeV<sup>2</sup> is the parameter in the harmonic oscillator wavefunction. The coupling of the  $S_{11}(1535)$  to  $\eta N$  in Eq. 2 is determined by the  $\eta NN$  coupling constant  $\alpha_\eta$ . This provides a consistency condition that must be checked in any microscopic model of baryon decay amplitudes, otherwise, the overall agreement with data from meson photoproduction would be lost. The coefficient  $C_{S_{11}(1535)}$  is equal to unity in the naive  $SU(6) \otimes O(3)$  quark model. Thus the quantity  $C_{S_{11}(1535)} - 1$  measures a deviation from the underlying  $SU(6) \otimes O(3)$  symmetry. Both the  $S_{11}(1535)$  and  $S_{11}(1650)$  resonances show a strong configuration mixing in more sophisticated models[12].

By treating the coupling constant  $\alpha_\eta$ , the coefficient  $C_{S_{11}(1535)}$  and the total decay width  $\Gamma_T$  as free parameters and fitting them to the experimental data, we find[7]

$$\begin{aligned} \Gamma_T &= 198 \text{ MeV} \\ C_{S_{11}(1535)} &= 1.608 \\ \alpha_\eta &= 0.435, \end{aligned} \quad (3)$$

which gives an excellent fit to the recent Mainz[5] data. The total width,  $\Gamma_T$ , obtained from the chiral quark model only differs from a simple Breit-Wigner parameterization by 4 to 5 MeV[5]. The above results give

$$\xi = 0.220 \text{ GeV}^{-1}. \quad (4)$$

This value is in good agreement with results of the RPI group, which used an effective Lagrangian approach to fit both old data sets and new data from the Mainz group[11, 13]. An extraction of the helicity amplitude  $A_{1/2}^p$  from the quantity  $\xi$  depends on the  $\eta N$  branching ratio  $\chi_{\eta N}$ , which is not precisely known at present. One could use, as a guide, the result from a recent coupled channel analysis by Batinić *et al*[2]. There the branching ratios to  $\eta N$  and  $\pi N$  channels

$$\chi_{\eta N} = 0.63 \text{ and } \chi_{\pi N} = 0.31, \quad (5)$$

were found for the  $S_{11}(1535)$  resonance, the latter being in good agreement with a result from the VPI group[1]. These lead to the helicity amplitude

$$A_{1/2}^p = 98.9 \cdot 10^{-3} \text{ GeV}^{-1/2}. \quad (6)$$

However, the total width  $\Gamma_T$  for the resonance  $S_{11}(1535)$  varies significantly when extracted from recent partial wave analyses[1, 2] and the  $\eta$  photoproduction data[5]. Therefore, the helicity amplitude  $A_{1/2}$  still cannot be extracted reliably, as it is proportional to  $\sqrt{\frac{\Gamma_T}{\chi_{\eta N}}}$  for a fixed quantity  $\xi$ .

There are two  $S_{11}$  resonances near 1.6 GeV in the quark model generated by the  $SU(6) \otimes O(3)$  basis. Discrepancies between the theory, in various quark model calculations, and the properties of the  $S_{11}(1535)$  resonance have been known for some time. The helicity amplitude  $A_{1/2}^p$  from quark model calculations has[14, 15] remained near  $150 \cdot 10^{-3} \text{ GeV}^{-\frac{1}{2}}$ , while the branching ratio for the  $S_{11}(1535)$  resonance decaying to  $\eta N$  is too small[7, 15]. The solution within the quark model has been configuration mixing between the two  $S_{11}$   $SU(6) \otimes O(3)$  states. However, our investigation of  $\eta$  photoproduction indicates that configuration mixing alone may not be enough to resolve this problem. The coefficient  $C_{S_{11}(1535)}$ , from fits to  $\eta$  photoproduction data in Ref. [7], is found to be  $1.5 \sim 1.6$ , suggesting that the naive quark model would predict

$$\xi \approx 0.14 \text{ GeV}^{-1}. \quad (7)$$

Notice that the quantity  $\xi$  is proportional to the product of the helicity amplitude  $A_{1/2}$  and the meson decay amplitude

$$\xi \propto \langle N | H_\eta | S_{11} \rangle \langle S_{11} | H_{em} | N \rangle. \quad (8)$$

Configuration mixing effects for the wavefunction of the  $S_{11}$  resonance and the nucleon are unlikely to increase the quantity  $\xi$ . This shows that the branching ratios for the  $S_{11}(1535)$  resonance have not been understood in the quark model. For the resonance  $S_{11}(1650)$ , the naive quark model predicts

$$\xi_{S_{11}(1650)} = 0. \quad (9)$$

This is consistent with the  $\eta$  photoproduction data but for the wrong reason. Eq. 9 comes from the Moorhouse selection rule[16] which predicts that the electromagnetic transition between the nucleon and the  $S_{11}(1650)$  resonance vanishes. In fact, while partial-wave analyses show that the  $\eta N$  branching ratio is very small, the helicity amplitude for the  $S_{11}(1650)$  is substantial. Both the Kent State[17] and Virginia Tech[1] analyses imply that the  $S_{11}(1650)$  resonance has a  $\Gamma_{\pi N}/\Gamma$  branching ratio approaching unity, making it the most elastic resonance apart from the  $P_{33}(1232)$ , a result consistent with the recent coupled channel analysis of Ref.[2].

Therefore, the enhancement of the  $S_{11}(1535)$  resonance and the suppression of the  $S_{11}(1650)$  resonance in the  $\eta N$  channel are certainly key to our

understanding of their underlying spin-flavor structure. This has motivated a number of different approaches to the problem. The investigation by Kaiser *et al.*[18] has indicated that a quasi-bound  $K\Sigma$  state with properties remarkably similar to the  $S_{11}(1535)$  may be responsible for the large  $\eta N$  branching ratio attributed to the  $S_{11}(1535)$  resonance. In the study of Ref.[18], an  $SU(3)$  effective chiral Lagrangian was applied to the S-wave meson-baryon interaction and the parameters were determined by low-energy  $\bar{K}N$  experimental data. The resonance  $\Lambda(1405)$ [19] has been suggested as a possible  $K$ -nucleon bound state whose mass is just below the  $KN$  threshold. It is certainly possible that there is a weakly bounded  $K\Lambda$  or  $K\Sigma$  state whose mass lies just below the  $K\Lambda$  or  $K\Sigma$  threshold. The problem with this approach is that data for the electromagnetic transition, in particular the  $Q^2$  dependence[20] of the helicity amplitude  $A_{1/2}^p$ , indicates that the  $S_{11}(1535)$  should be a dominantly 3-quark state at higher  $Q^2$ , according to the perturbative QCD counting rule[21]. Thus, if such a quasi-bound  $K\Sigma$  state exists, it should be strongly mixed with the 3-quark configurations. This requires an additional  $S_{11}$  resonance with a mass near the two known  $S_{11}$  resonances predicted by the quark model.

Therefore, a quasi-bound  $K\Lambda$  or  $K\Sigma$  state is possible only if a third  $S_{11}$  resonance exists near the two known  $S_{11}$  resonances, and there is considerable experimental evidence for this extra  $S_{11}$ . The most recent VPI analysis of  $\pi N$  elastic scattering[1] claims some evidence for a third  $S_{11}$  resonance with mass and decay width

$$M_{S_{11}} = 1.712 \quad \Gamma_{S_{11}} = 0.184 \quad (10)$$

in GeV units. A similar structure was found[22] by Höhler in his speed plot of the KA84 solution, although he did not consider this to be a resonance. In addition to the analysis of  $\pi N$  elastic scattering data, the coupled channel analysis of  $\pi N \rightarrow \eta N$  and  $\eta N \rightarrow \eta N$ [2] results in a solution consistent with the presence of a third  $S_{11}$  resonance with a mass of 1.705 GeV and total width 0.27 GeV. (This state was identified as the  $S_{11}(2090)$ .) In fact, this new  $S_{11}$  resonance may already have been seen in a much older partial wave analysis of the reaction  $\pi N \rightarrow K\Sigma$ [23], where the  $S_{11}$  resonance had a fitted mass of  $1.70 \sim 1.75$  GeV and a total width  $0.210 \sim 0.270$  GeV.

More experimental evidence is certainly needed to establish this resonance. As the new state is only slightly above the  $S_{11}(1650)$ , it would be difficult to determine which is contributing to a particular reaction. However, if the VPI and Kent State[1, 17] analyses are correct, the  $S_{11}(1650)$  resonance should not contribute strongly to reactions having initial and final states other than  $\pi N$ , a view supported by the analysis of Batinić *et al.*[2]. Furthermore, the partial

wave analysis of  $\pi N \rightarrow K\Sigma$  by Deans *et al.*[23] suggests that the coupling of this resonance to the  $K\Sigma$  final state is quite strong. Thus kaon production experiments, such as  $\pi N \rightarrow KY$ , and  $\gamma N \rightarrow KY$ , would be important in establishing its existence.

In addition to a strong coupling to the  $K\Sigma$  final state, the contribution from this resonance would be further enhanced by threshold effects. To understand why this is the case, we show the relation between the masses of the S-wave resonances, which include  $\Lambda(1405)$ ,  $S_{11}(1535)$ ,  $S_{11}(1650)$  and  $S_{11}(1710)$ , and the threshold energies of  $\eta$  and kaon production, which include  $KN$ ,  $\eta N$ ,  $K\Lambda$  and  $K\Sigma$  channels in Fig. 1. The S-wave resonances are clearly sandwiched between the threshold energies of  $\eta$  and  $K$  productions. Our investigations of meson photoproduction show[7, 8] that there are two major factors determining the threshold behaviour, the leading Born terms which are dominated by the contact (seagull) term, and the S-wave resonances whose masses are near the threshold energies shown in Fig. 1. The contact term is proportional to the charge of the photoproduced meson and the form factors, generated by the spatial wavefunctions, predict a forward peaking behavior. This is confirmed by data[24] for the  $\gamma p \rightarrow K^+\Lambda$  reaction. On the other hand, the leading contact term does not contribute to the photoproduction of neutral mesons, thus the role of S-wave resonances near the threshold region is enhanced. This is one of the major reasons that the  $S_{11}(1535)$  resonance dominates the threshold region in  $\eta$  photoproduction. The calculation of  $\gamma p \rightarrow \eta p$ [7] shows that the  $S_{11}(1535)$  resonance still dominates the threshold region even with a smaller  $\xi$  consistent with the quark model prediction. Note that the resonances  $S_{11}(1535)$  and  $S_{11}(1710)$  are just above the  $\eta N$  and  $K\Lambda$  or  $K\Sigma$  threshold energies respectively. A similar behavior should be found in  $K^0$  production, such as  $\gamma n \rightarrow K^0\Lambda$  and  $\gamma p \rightarrow K^0\Sigma^+$ , in which the resonance  $S_{11}(1710)$  would play the same role in  $K^0$  photoproduction as the  $S_{11}(1535)$  resonance in  $\eta$  photoproduction. Therefore, we expect that the  $S_{11}(1710)$  resonance will be enhanced in threshold  $K^0$  production if such a state exists. More precise data for  $\pi N \rightarrow KY$  would also be needed for a systematic study of its properties.

In summary, we have shown that there is considerable evidence suggesting the existence of a third  $S_{11}$  resonance with a mass near 1.7 GeV. This might be the key to our understanding of the enhancement of the  $S_{11}(1535)$  and suppression of the  $S_{11}(1650)$  in the  $\eta N$  channel. We suggest that a third  $S_{11}$  resonance would support the existence of a quasi-bound  $K\Sigma$  or  $K\Lambda$  state, and kaon production experiments, in particular  $\gamma p \rightarrow K^0\Sigma^+$  and  $\gamma n \rightarrow K^0\Lambda$ ,  $K^0\Sigma^0$ , would be very sensitive to this resonance. The existence of a third  $S_{11}$  resonance would certainly provide challenges to the theory, suggesting that the

quark model must incorporate chiral dynamics in order to provide a consistent treatment of the  $S_{11}$  resonances. Future experiments at CEBAF[25] and ELSA will provide us more information in this regard.

This work was supported in part by the U.S. Department of Energy Grant DE-FG05-88ER40454, and the U.S. National Science Foundation grant PHY-9023586.

## References

- [1] R.A. Arndt, I.I. Strakovsky, R.L. Workman, and M.M. Pavan, Phys. Rev. C 52, 2120 (1995).
- [2] M. Batinic, I. Slaus, A. Svarc, and B.M.K. Nefkens, Phys. Rev. C 51, 2310 (1995).
- [3] S. Dytman *et al.*, Phys. Rev. **C51**, 2170(1995).
- [4] J. Price *et al.*, Phys. Rev. **C51**, R2283(1995).
- [5] B. Krusche *et al.*, Phys. Rev. Lett. **74**, 3736(1995).
- [6] Zhenping Li, Phys. Rev. **D50**, 5639(1994).
- [7] Zhenping Li, Phys. Rev. **D52**, 4961(1995).
- [8] Zhenping Li, Phys. Rev. **C52**, 1648(1995).
- [9] A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189(1984).
- [10] D. Drechsel and L. Tiator, J. Phys. **G48**, 449(1992).
- [11] M. Benmerrouche, N. C. Mukhopadhyay, and J. F. Zhang, Phys. Rev. **D51**, 3237(1995). M. Benmerrouche and N. Mukhopadhyay, Phys. Rev. Lett. **67**, 101(1992).
- [12] N. Isgur and G. Karl, Phys. Lett. **72B**, 109(1977), Phys. Rev. **D18**, 4187(1978).
- [13] N. C. Mukhopadhyay, *et al.*, "Photoproduction of etas and  $N^*(1535)$  electrostrong properties", nucl-th/9511001.

- [14] F. E. Close and Zhenping Li, Phys. Rev. **D42**, 2194(1990); Phys. Rev. **D42**, 2207(1990).
- [15] R. Koniuk and N. Isgur, Phys. Rev. **D21**, 1888(1980).
- [16] R. G. Moorhouse, Phys. Rev. Lett. **16**, 772(1966).
- [17] D.M. Manley and E.M. Saleski, Phys. Rev. D 45, 4002 (1992).
- [18] N. Kaiser, P.B. Siegel, and W. Weise, “Chiral Dynamics and the  $S_{11}(1535)$  Nucleon Resonance”, nucl-th/9507036, to appear on Phys. Lett. B.
- [19] See the note by R.H. Dalitz in the Review of Particle Properties, Phys. Rev. D 50, 1732 (1994). N. Kaiser, P. B. Siegel, and W. Weise, “Chiral Dynamics and the Low Energy Kaon Nucleon Interaction”, Nucl. Phys. A. (1995), in press, nucl-th/9505043.
- [20] P. Stoler, Phys. Rev. Lett. **66**, 1003(1991); Phys. Rev. **D44**, 73(1991).
- [21] C. E. Carlson and N. C. Mukhopadhyay, Phys. Rev. Lett. **67**, 3745(1991), and references therein.
- [22] G. Höhler, Proc. of the 5th Meson-Nucl. Symp. Boulder, Colorado, USA, Sept. 1993, Eds. B. M. K. Nefkens and M. Clajus,  $\pi N$  Newslett. **9**, 1(1993).
- [23] S.R. Deans, R.W. Mitchell, D.L. Montgomery, G.C. Wood, and J.E. Rush, Nucl. Phys. B96, 90 (1975).
- [24] R. A. Adelseck and B. Saghai, Phys. Rev. **C42**, 108(1990).
- [25] R. Schumacher, CEBAF proposal E89-004, unpublished.



## Figure Caption

1. Location of S-wave resonances and the threshold energies for  $KN$ ,  $\eta N$ ,  $K\Lambda$  and  $K\Sigma$  production.